



# **Fluid Structure Interaction in a Cold Flow Test and Transient CFD Analysis of Out-of-Round Nozzles**

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# Overview

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## Two Related Topics Presented

- A cold flow nozzle test with fluid-structure interaction when the nozzle had separated flow
- CFD analysis for nozzle flow and side loads of nozzle extensions that are out-of-round.



# **First Topic: Fluid Structure Interaction**

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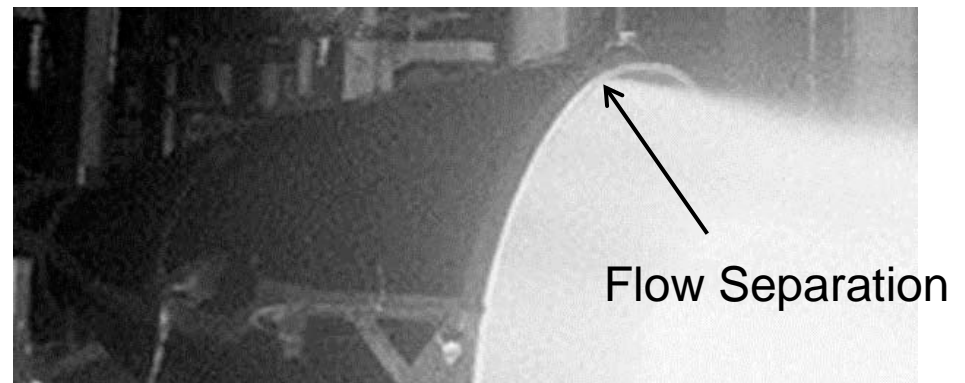


**Material From:**  
**“Characterization of Side Load Phenomena using  
Measurement of Fluid/Structure Interaction”,  
AIAA-2002-3999**

**Joint Propulsion Conference  
July, 2002**

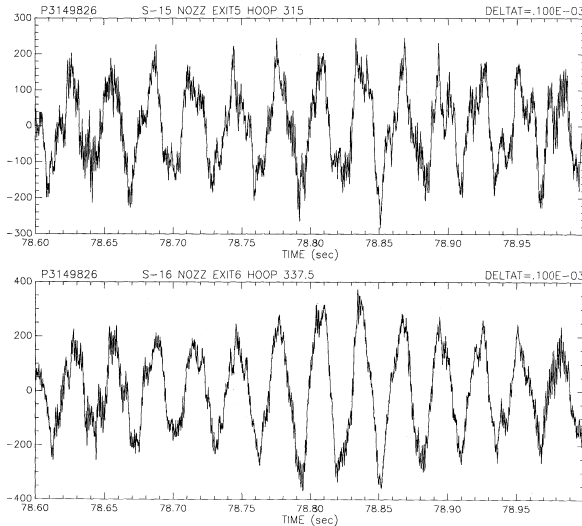
**Dr. A. Brown, J. Ruf  
NASA/Marshall Space Flight Center  
&  
Dr. R. Keanini of UNC Charlotte**

- ◆ The FASTRAC engine was an LOX-RP1 engine designed in-house at MSFC in the mid 1990's.
- ◆ Stub nozzle test shown, full nozzle was longer as it was an altitude engine.
- ◆ The stub did not flow full at sea level. Flow separation clearly identified.
- ◆ Flow separated for the full duration of the test.
- ◆ Strain-gauge measurements taken on nozzle during hot fire test.

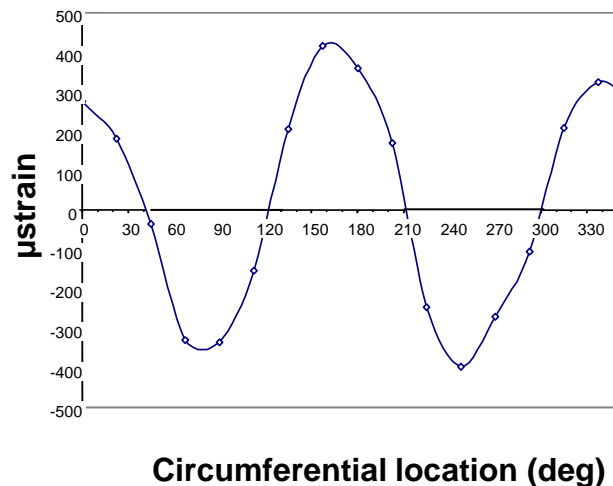


- ◆ Nozzle 2ND mode dominated the nozzle's response.
- ◆ Strain gages were at 16 circumferential locations

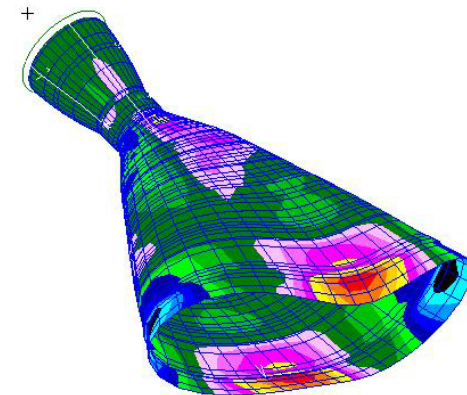
2 strain time histories



Circumferential strain map at time t

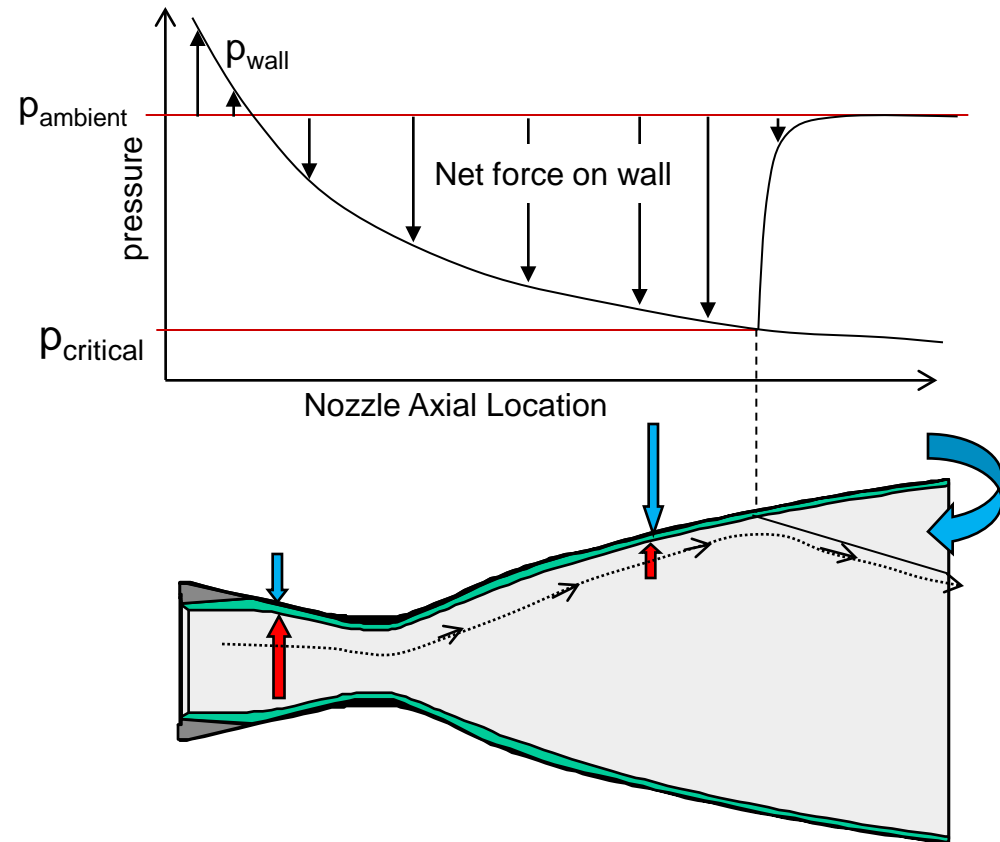


2ND mode (From finite element analysis)

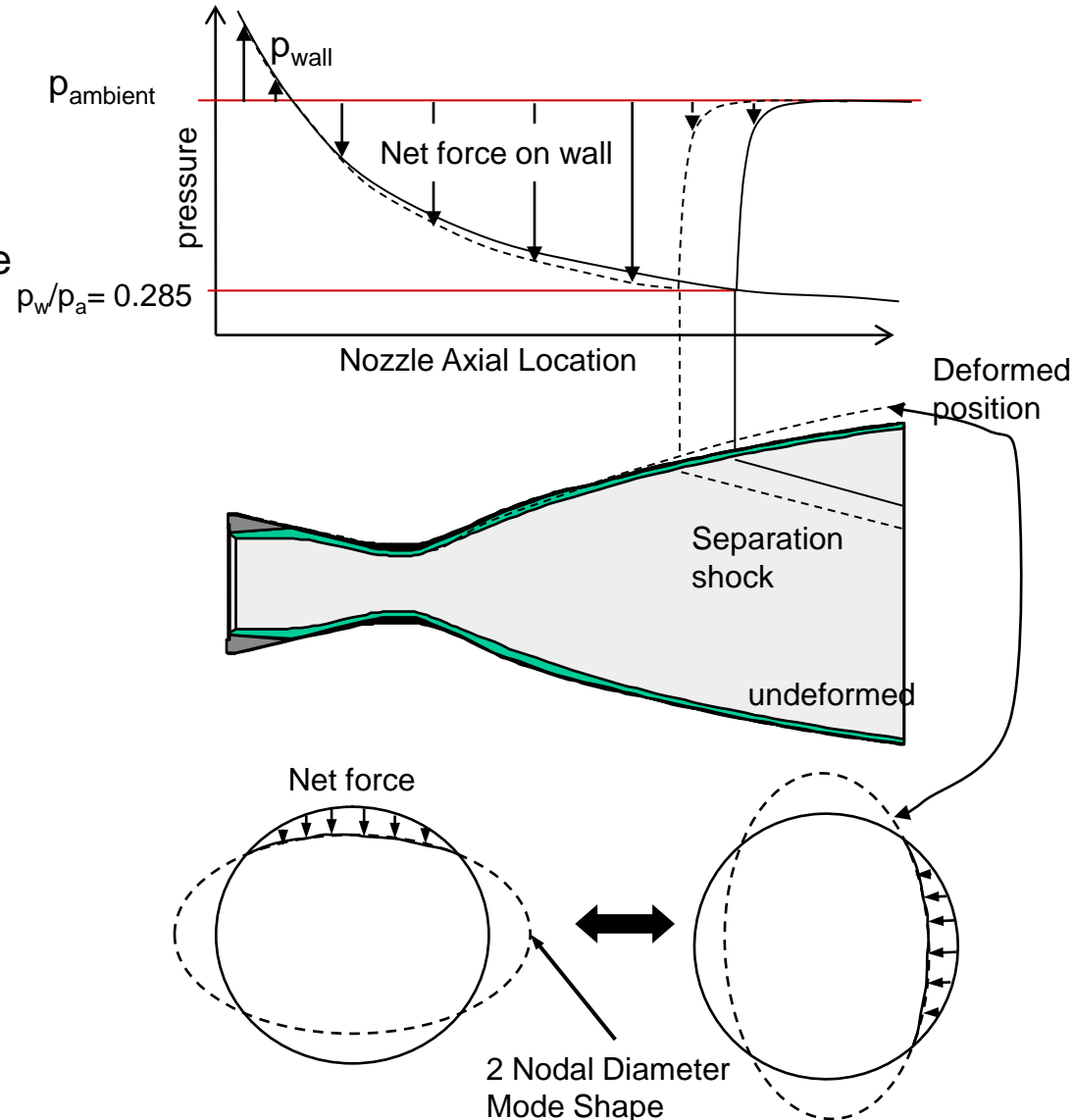


- Not conclusive evidence of fluid structure interaction since combustion excites all modes
- Clear that further testing, study, analysis required to produce useful design and analysis methodologies.

- ◆ Ground tested rocket engine nozzles generally operate in overexpanded condition.
- ◆ Overexpansion causes boundary layer separation of low-pressure internal fluid flow from inner wall of nozzle
- ◆ Separation is not axisymmetric. Asymmetric loads are generated.
- ◆ These asymmetric “side loads” have caused problems most liquid rocket engines at some point.
- ◆ Side loads typically a large factor in the design of the nozzle and interfacing hardware.



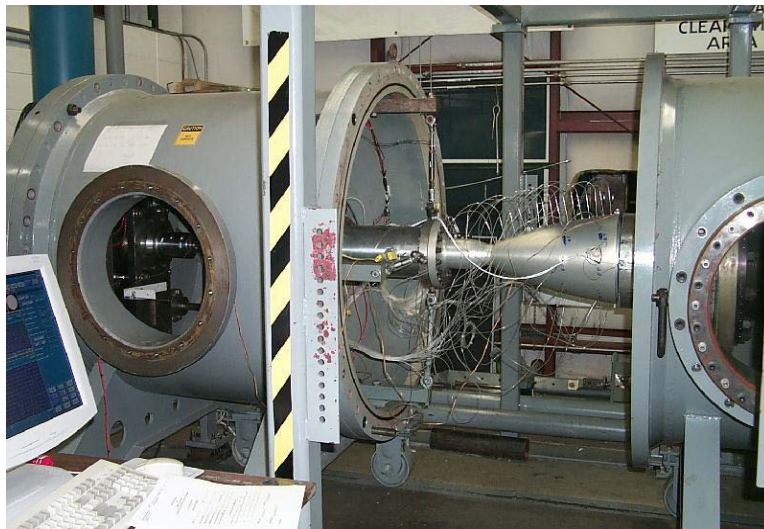
- ◆ Side load for FASTRAC nozzle were estimated with an empirical extrapolation.
- ◆ Conservative assumptions in the side load estimate lead to predicted hardware failure.
- ◆ Hypothesis: Loading caused by self-excited vibration of 2ND mode interacting with flow separation from wall.
- ◆ Research program initiated that included a cold flow test of a nozzle.





## Cold flow test of FASTRAC nozzle contour

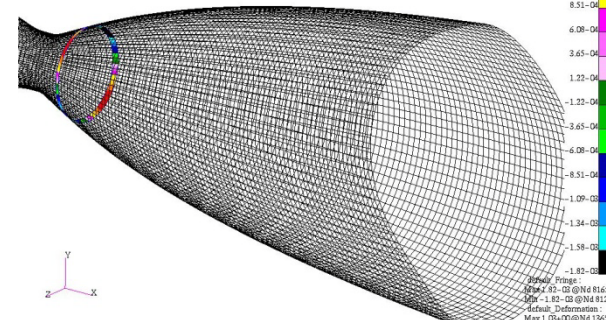
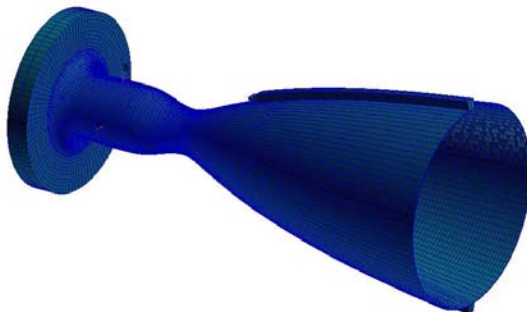
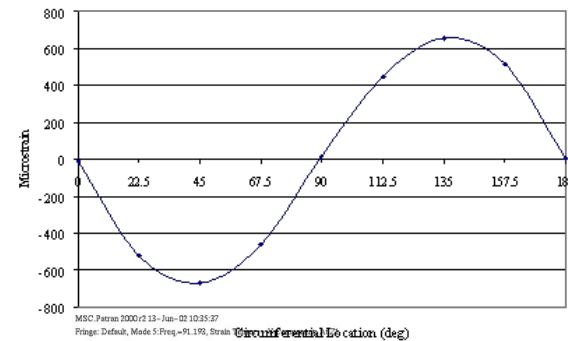
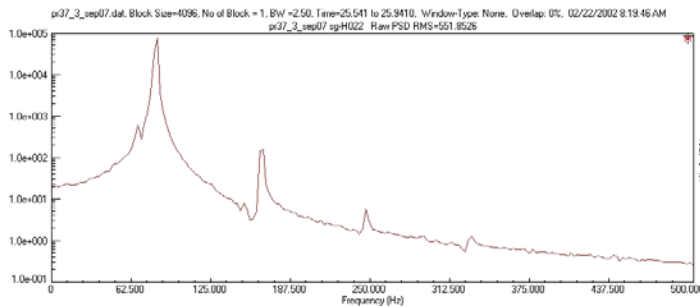
- Two test articles were fabricated.
  - One 'rigid', with a thick wall, ~25mm.
  - One 'flexible', with a wall that tapered to ~0.6mm
- Both had Ideal nozzle contour.
- Test articles were instrumented with static pressures, high frequency pressure, strain gages and accelerometers.





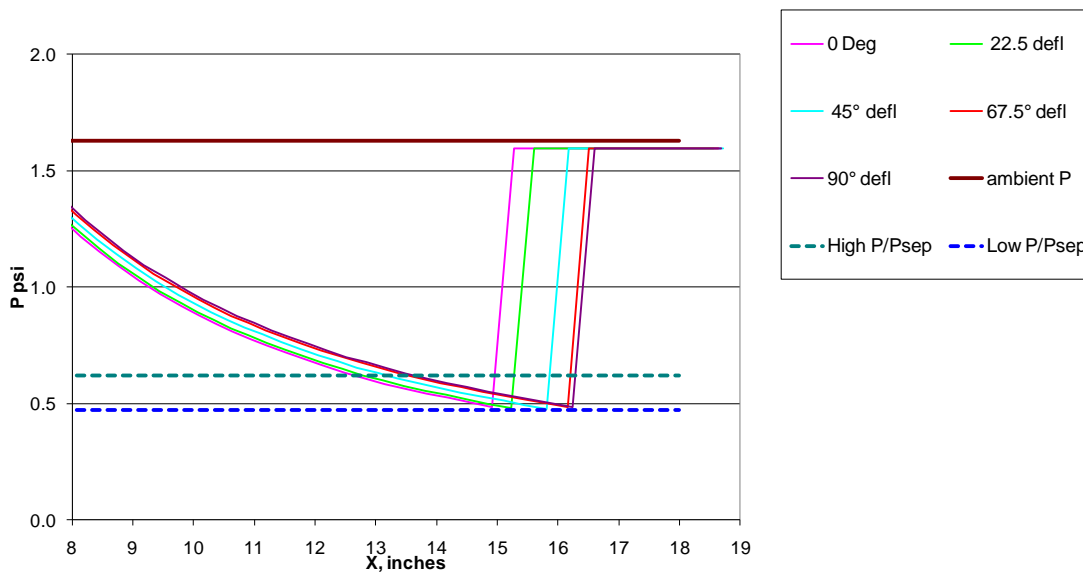
## Thin wall test article vibrated so hard it caused a strain gage 'red-line' cut off.

- At  $P_c = 12.2$  atm, (180 psia), NPR=110.
- Video and other data indicate extremely large vibration of 2ND mode.

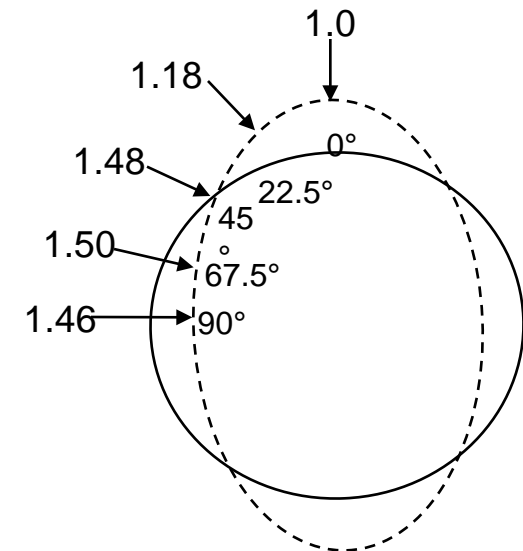


- Overexpanded flow produces radial inward forces on the aft end.
- With separated flow the radial inward force changes significantly.
- When the shape of the nozzle changes, the separation location moves forward or aft.
- A system of non-restoring forces arise that could couple with the structural dynamics.

Wall pressure profile from axisymmetric CFD for different amounts of wall deflection.



Normalized forces at difference azimuths.





**Material From:**  
**“Transient Three-Dimensional Side Load Analysis  
of Out-of-Round Film Cooled Nozzles”,  
AIAA-2010**

**Joint Propulsion Conference  
Aug, 2010**

**Dr. Ten-See Wang, J. Ruf  
NASA/Marshall Space Flight Center**



## Side loads and Motivations



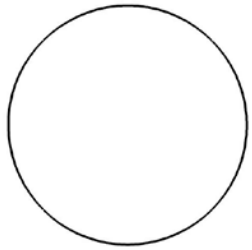
- UNIC CFD code has been used to calculate J-2X flow evolution and resulting nozzle side loads under various operating conditions and environments. One of the potential issues currently being explored is the effect of deformation of the nozzle.
- Liquid rocket engine nozzles, being large with relatively light weight structures, are probably never truly round. The cause of out-of-roundness could be, but are not limited to, the following:
  - asymmetric loads induced by hardware attached to the nozzle
  - asymmetric material internal stresses induced in previous tests, and nozzle wall material deformation, such as creep, incurred in previous engine tests
- In a round nozzle, side forces arise from asymmetric shock evolutions.
- Questions were raised about how nozzle deformation would affect the nozzle side load characteristics.



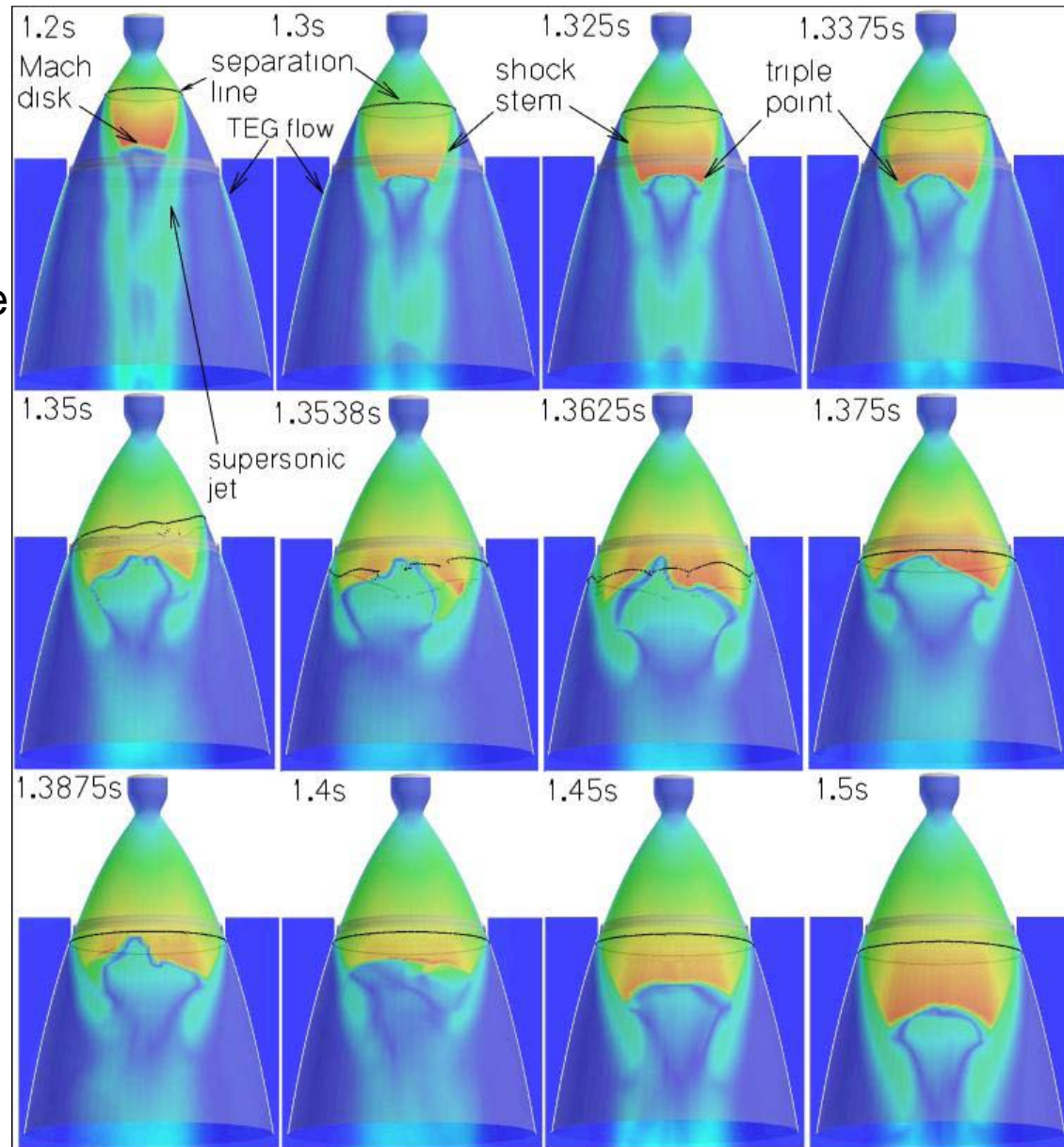
## Objective and Approach



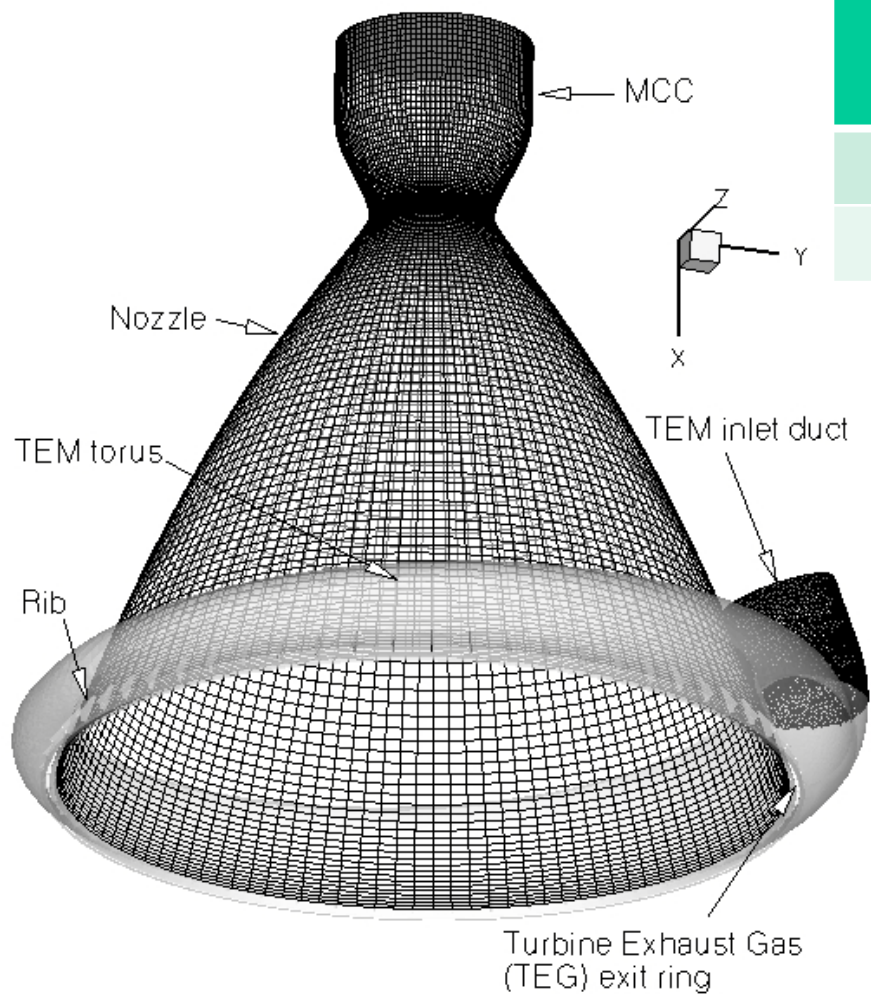
- Objective:  
To gain insight into side load characteristics of out-of-round nozzles
- Approach:  
Transient 3D UNIC CFD analyses were performed of the J-2X nozzle flow during the transient startup process on ovalized nozzles with a back pressure equivalent to 100,000 ft. Four nozzles with different degrees of ovalization were used to study the effect of out-of-roundness:
  - a perfectly round, or nominal nozzle,
  - a slightly ovalized nozzle,
  - a more ovalized nozzle, and
  - a significantly ovalized nozzle.



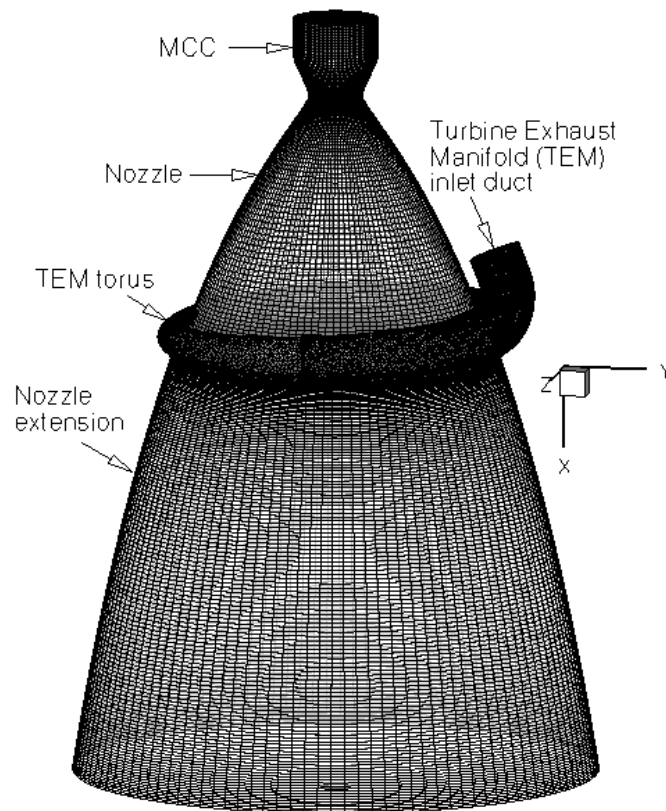
Circular separation line





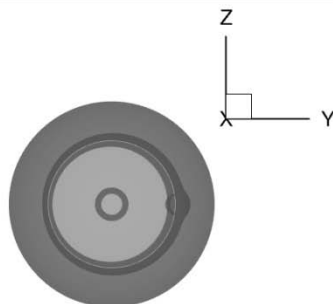


Engine	Grid size	Number of Azimuthal Planes
SSME	1,275,120	72
J-2X	4,421,166	120

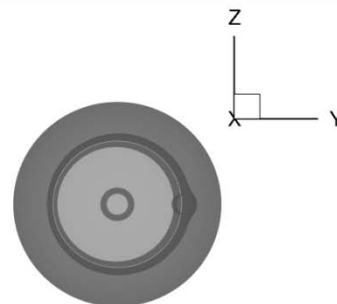




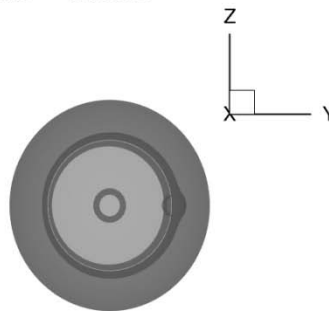
Case	Description	L/S	Deformation at end of Nozzle, in
1	Perfectly round	1.0000	$\pm 0.00$
2	Slightly out-of-round	1.0086	$\pm 0.25$
3	More out-of-round	1.0346	$\pm 1.00$
4	Significantly out-of-round	1.4400	$\pm 11.6$



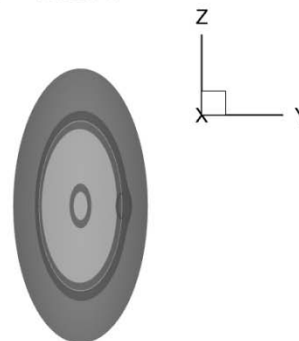
Case 2: L/S = 1.0086



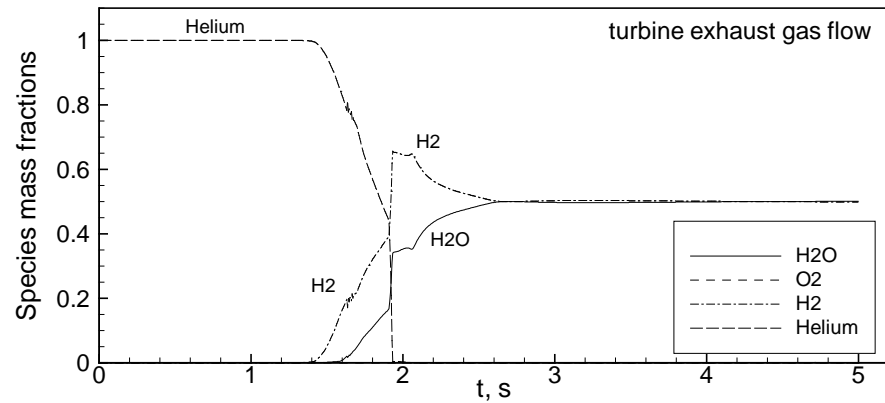
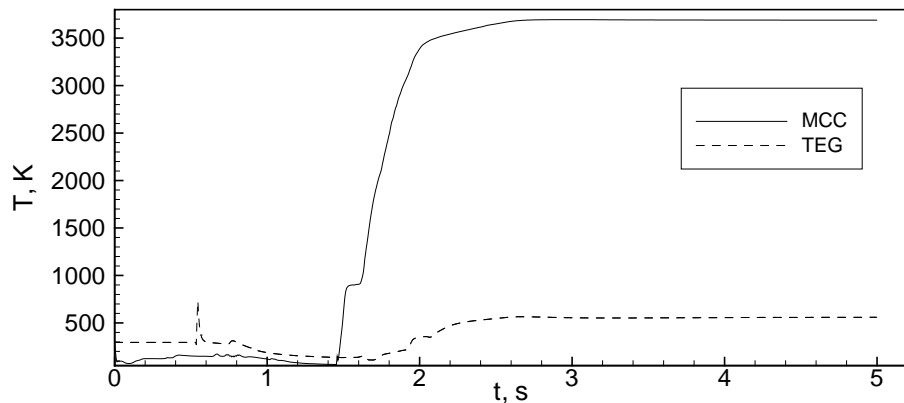
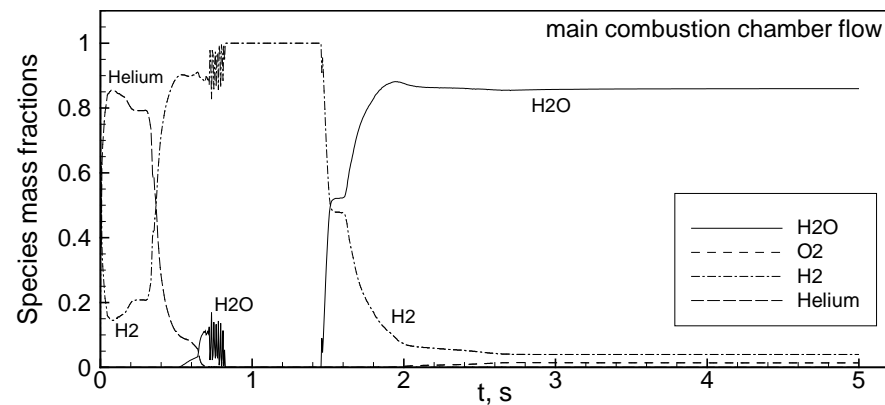
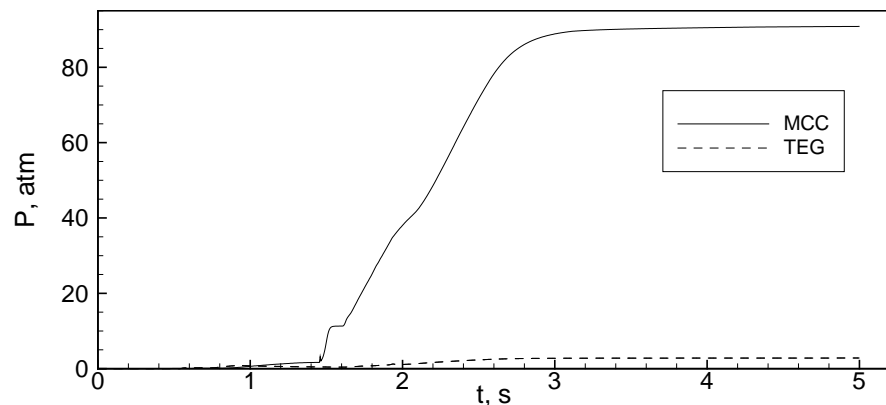
Case 1: L/S = 1.0000



Case 3: L/S = 1.0346



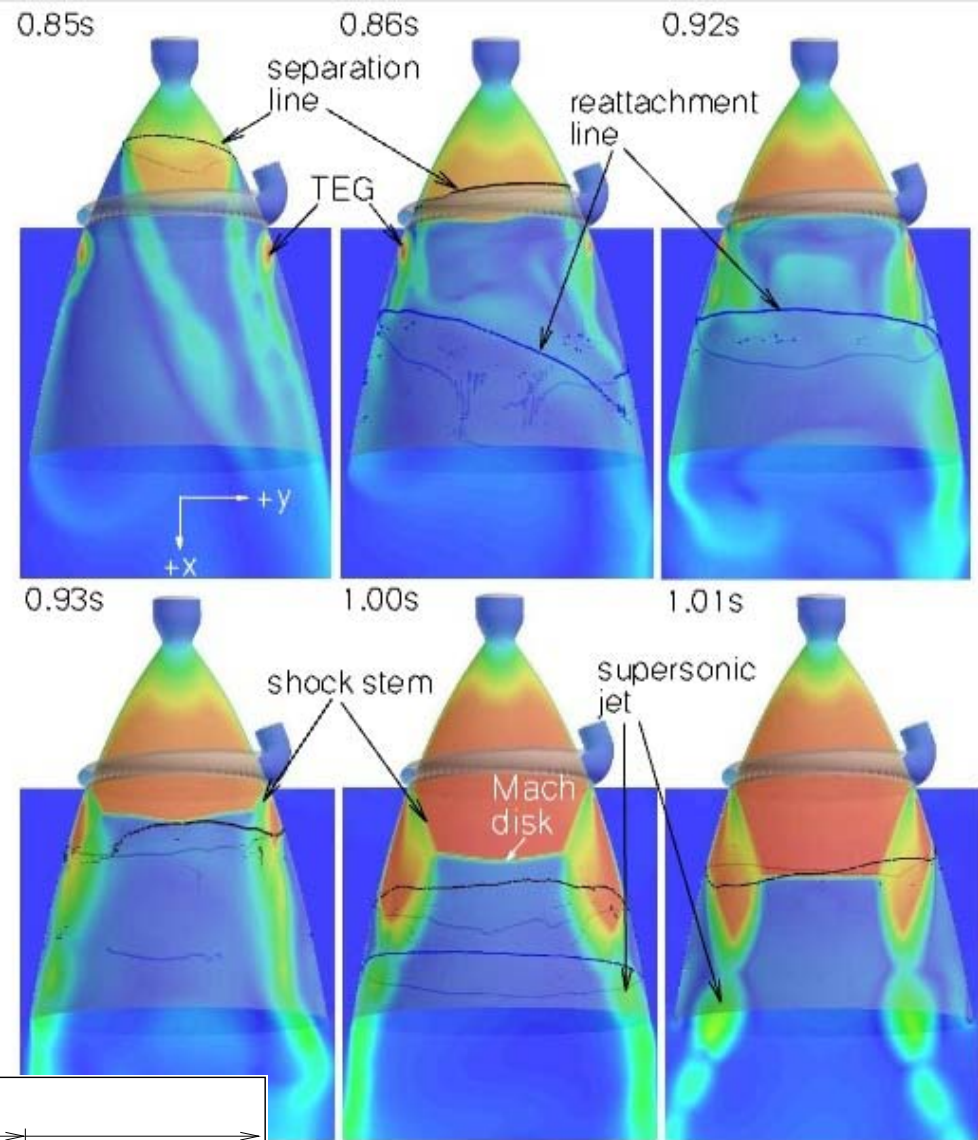
Case 4: L/S = 1.4400



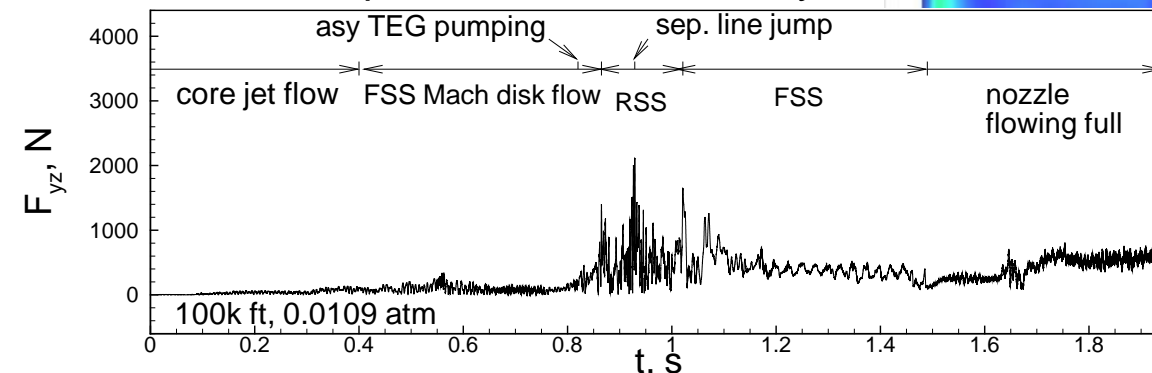


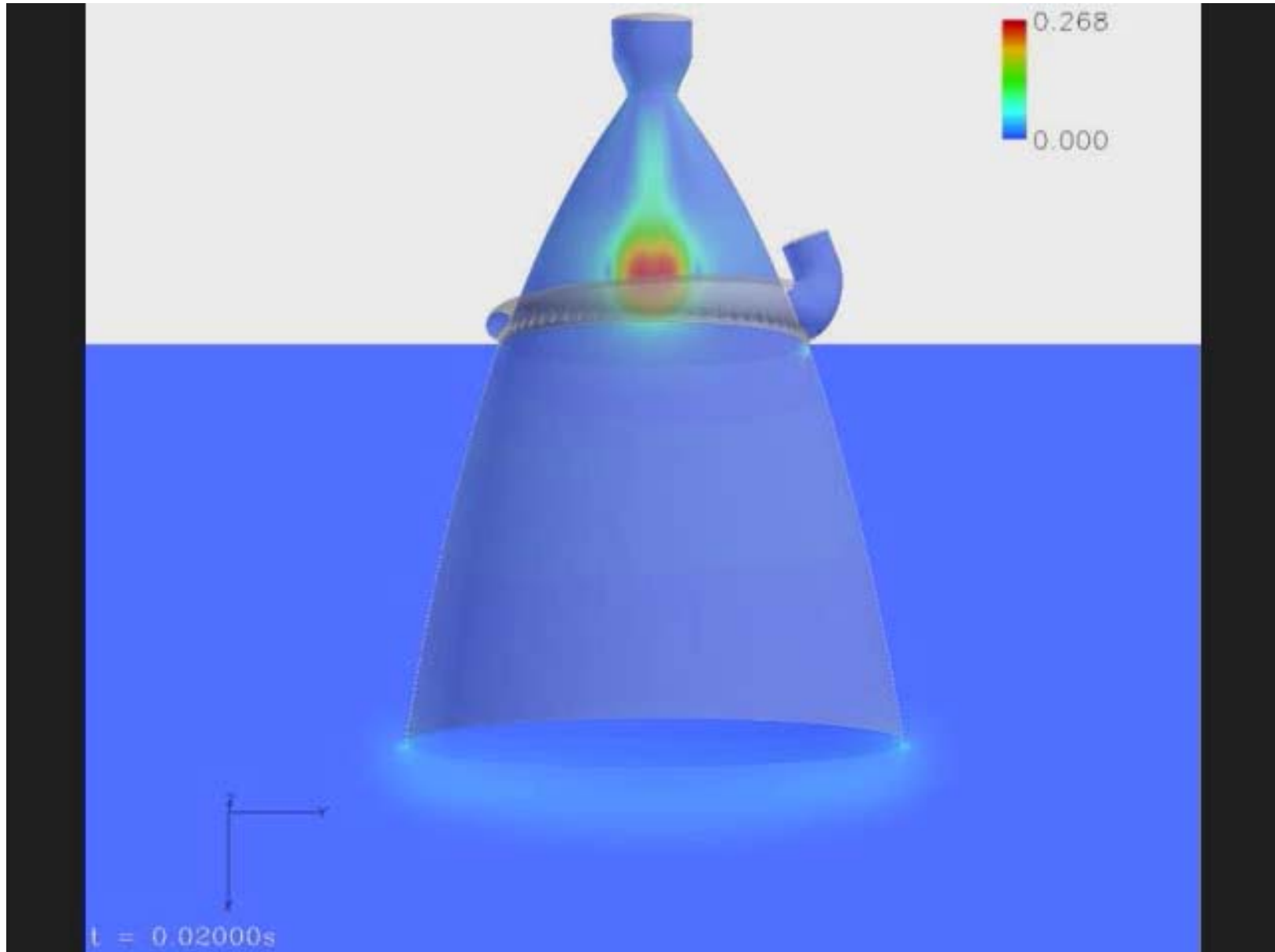
# Mach Contours for the Nominal Case

FSS	0.400s
TEG pumping	0.820s
FSS --> RSS	0.865s
Sep line jump	0.929s
RSS --> FSS	1.010s
Flowing full	1.490s

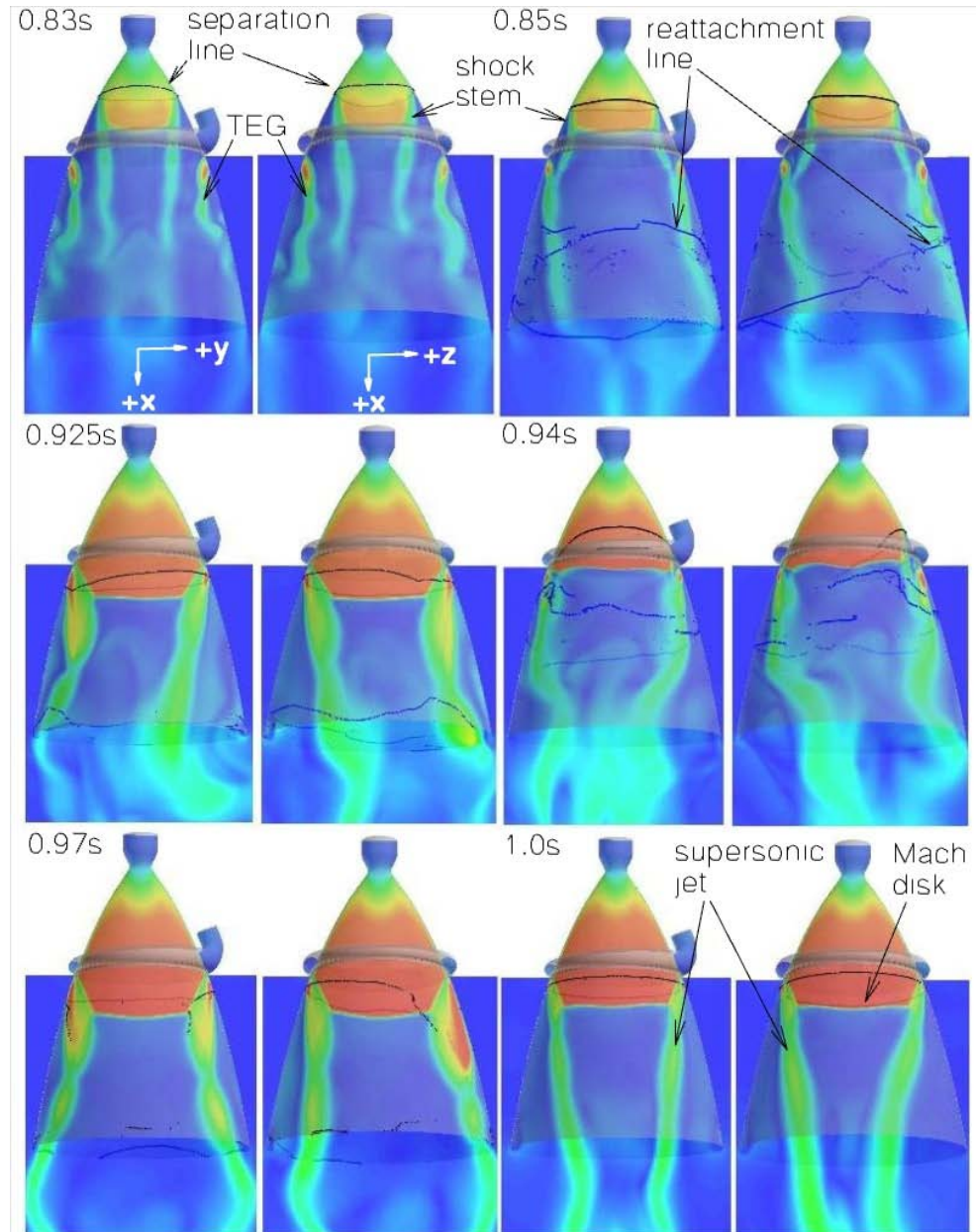


## Computed Side Load History



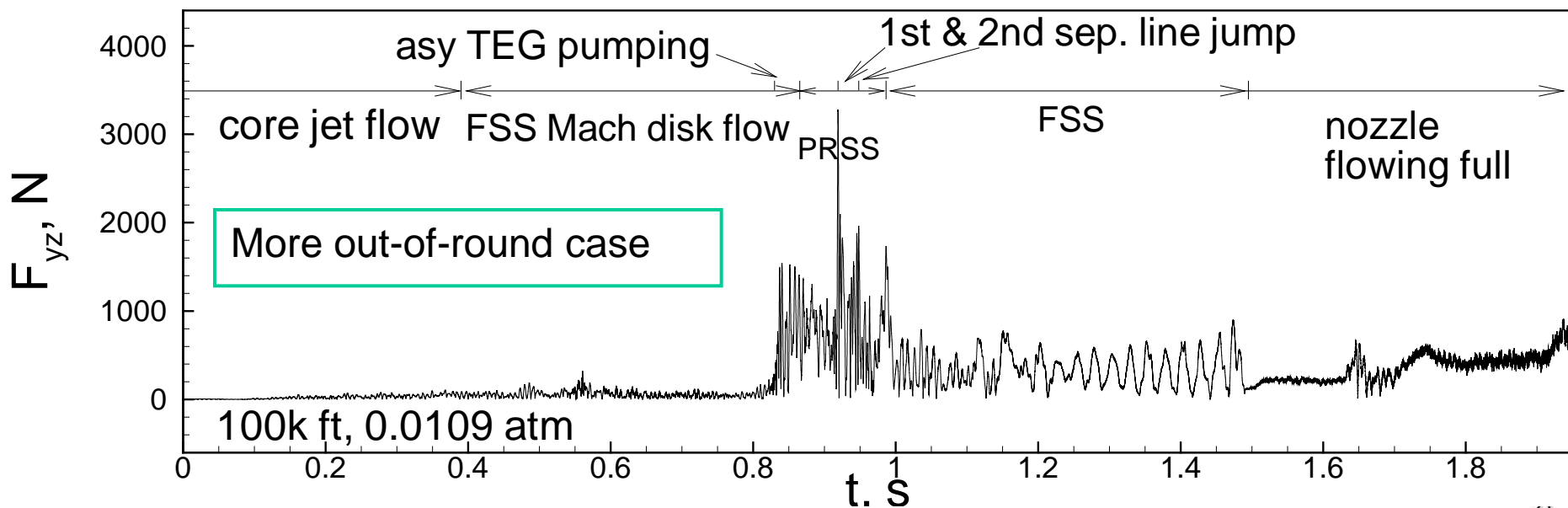
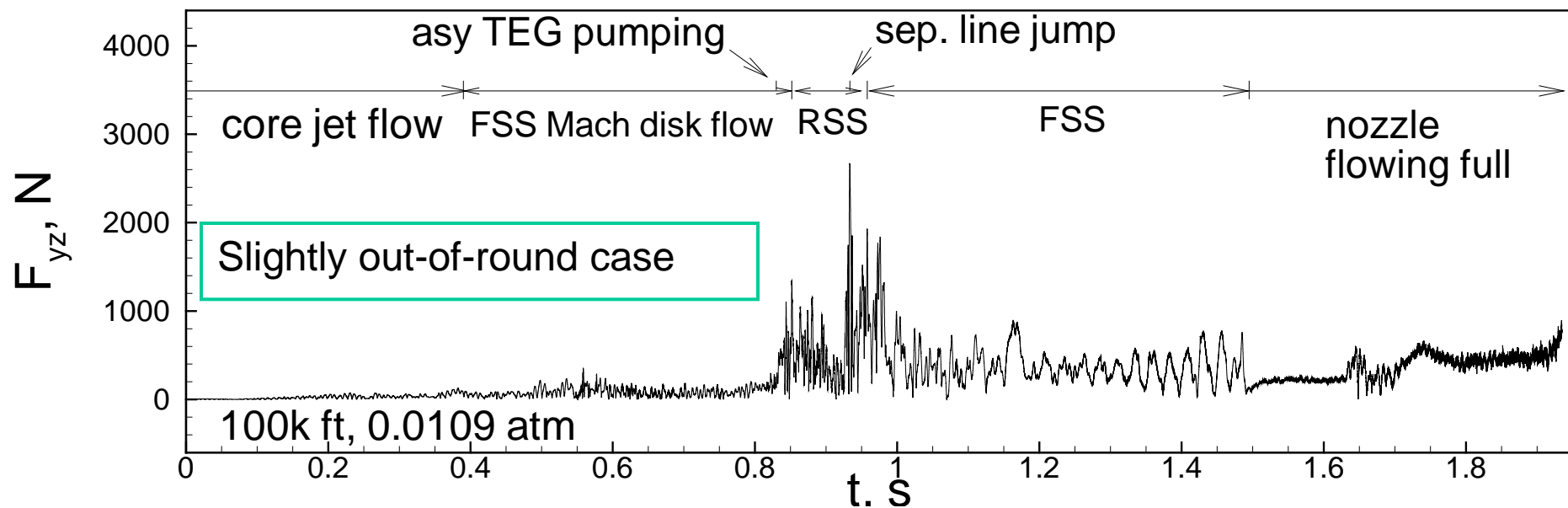


FSS	0.3900s
TEG pumping	0.8300s
FSS --> PRSS	0.8653s
1 <sup>st</sup> sep line jump	0.9191s
2 <sup>nd</sup> sep line jump	0.9481s
PRSS --> FSS	0.9865s
Flowing full	1.4950s



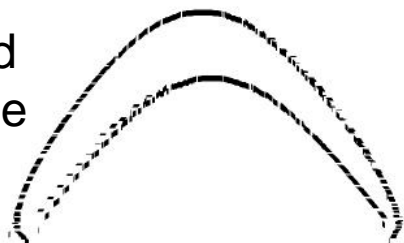


# Computed Side Load Histories

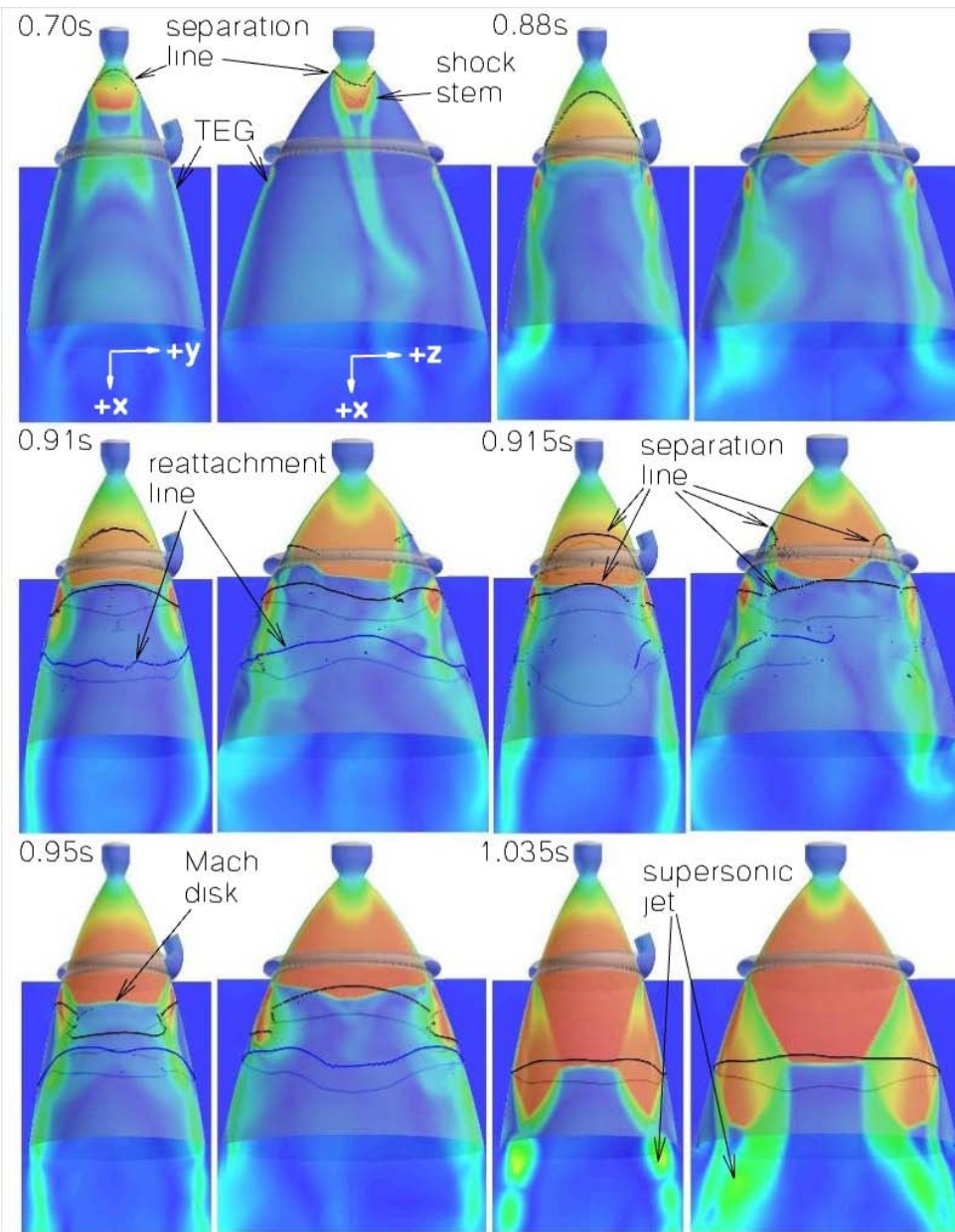




Sickle-shaped separation line at 0.70 s



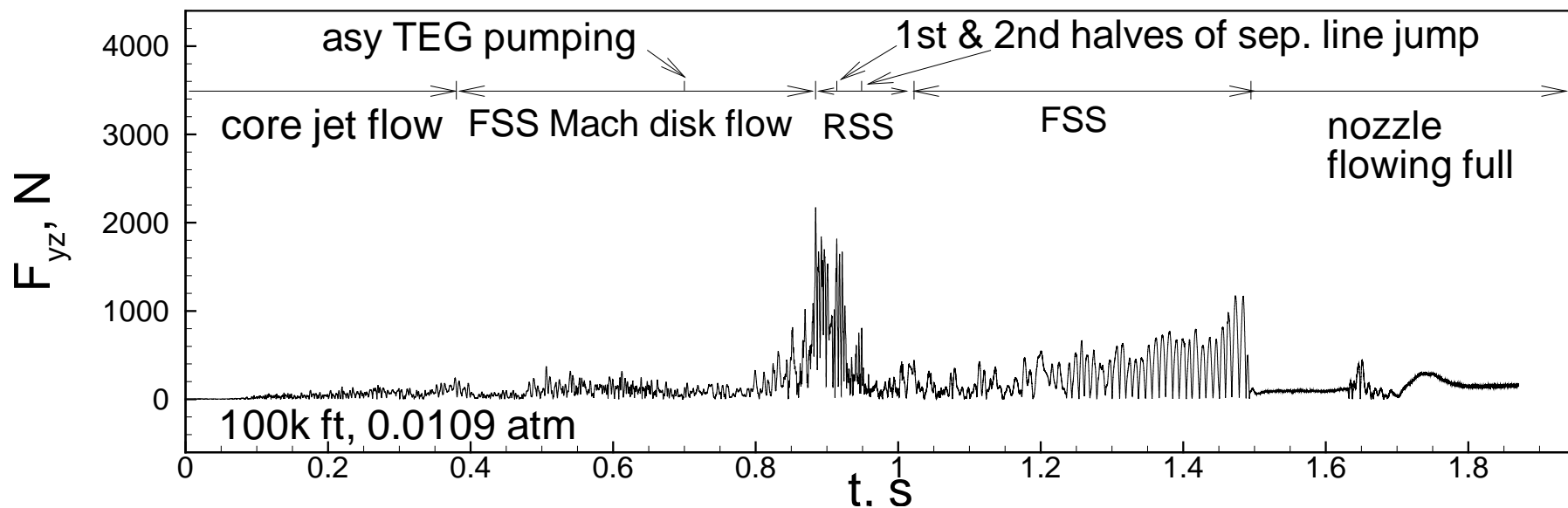
FSS	0.38000s
TEG pumping	0.70000s
FSS --> PRSS	0.88420s
1 <sup>st</sup> half SLJ	0.91387s
2 <sup>nd</sup> half SLJ	0.94883s
PRSS --> FSS	1.02223s
Flowing full	1.49500s







# Computed Side Load Histories for the Significantly Out-of-Round Case





## A Comparison of the Computed Peak Side Loads



Nozzle shape	Peak Fyz, N	Physics
Perfectly round	2114	Separation line jump
Slightly out-of-round	2668	Separation line jump
More out-of-round	3275	Separation line jump
Significantly out-of-round	2171	FSS-to-RSS transition



## Conclusions



Peak side load physics for the round, slightly out-of-round, and more out-of-round cases is the separation line jump, and that the peak side load increased as the degree of out-of-roundness increased.

For the significantly out-of-round case, the separation line jump was split into two parts. The peak side load was reduced to a level comparable to that of the round nozzle. This peak side load reduction mechanism, splitting the peak side load in azimuth, is consistent with experimental results reported for non-round polygon nozzles.



# BACKUP SLIDES

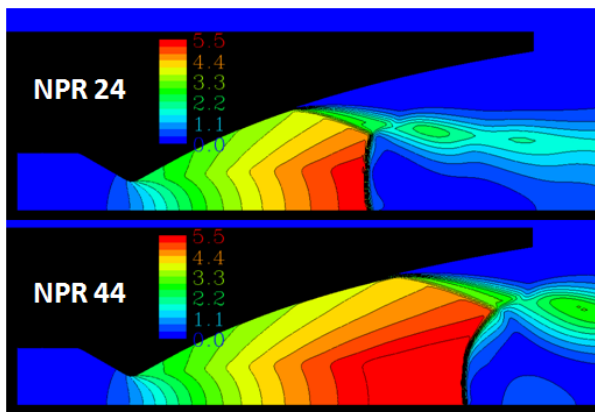
## Side Loads in a TIC

- FSS to qRSS early in the transient.
- Oscillation of the separation line

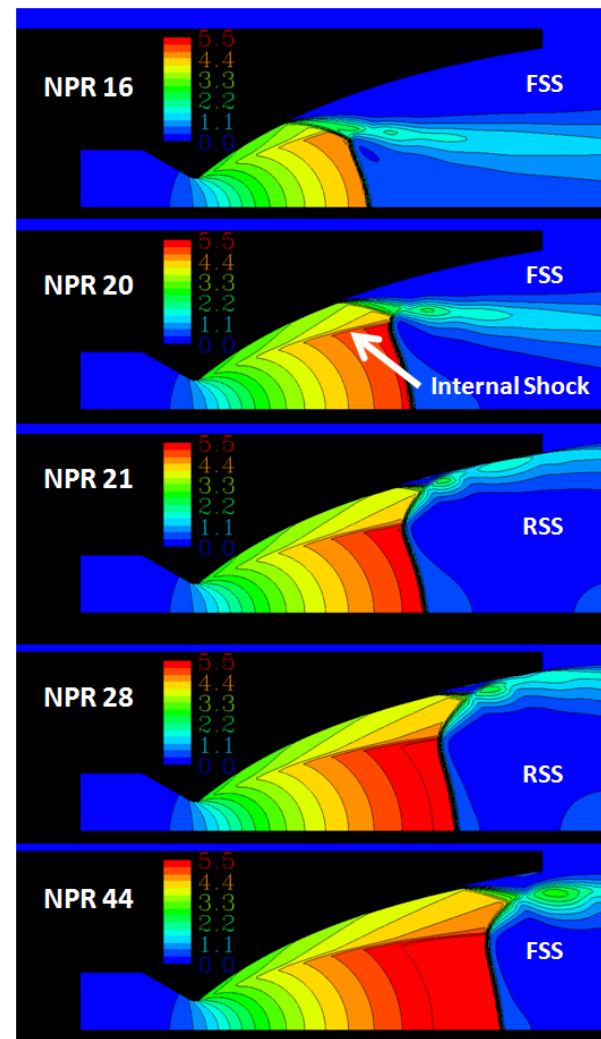
## Side Loads in a TOC

- Transition FSS to RSS
- Transition RSS to FSS

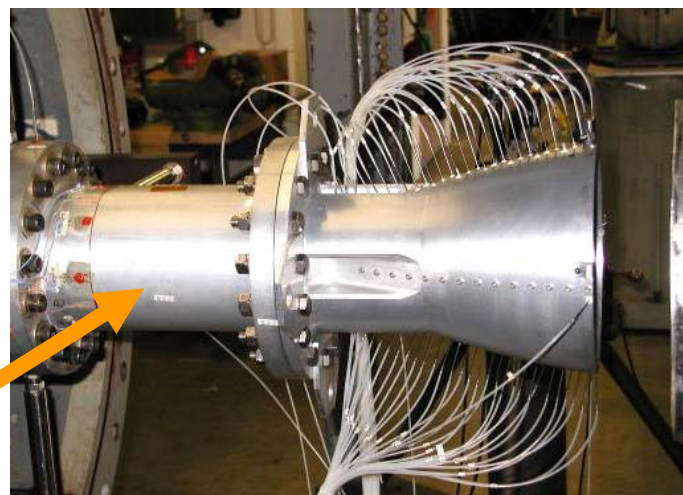
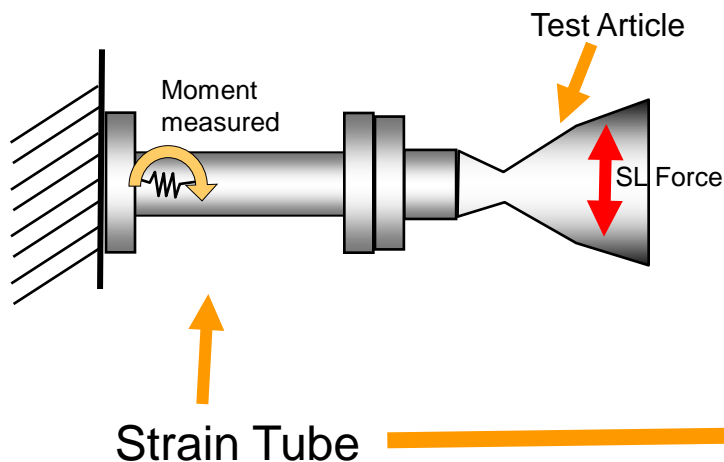
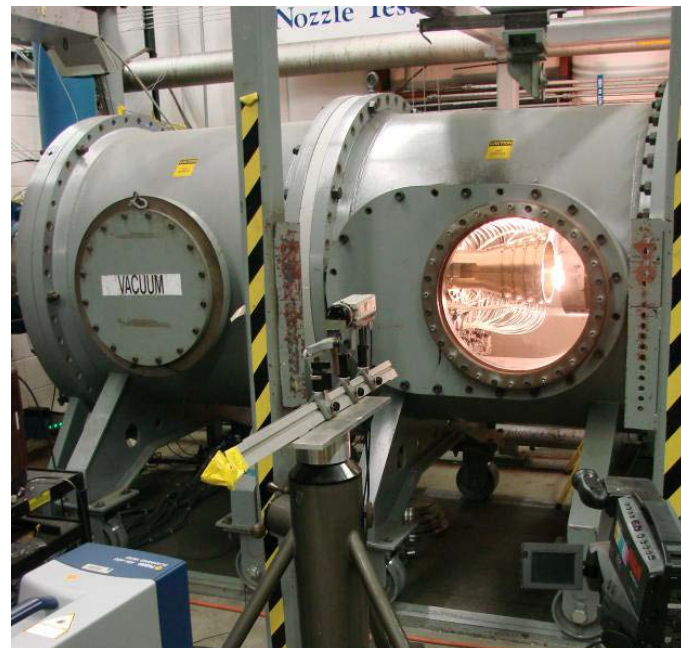
TIC



TOC



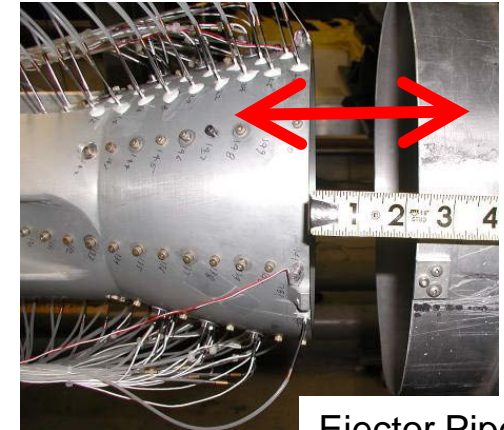
- ♦ The test facility available was a vacuum test chamber, MSFC's cold flow Nozzle Test Facility (NTF). Normal use was for measurement of axial thrust of nozzle test articles.
- ♦ Measured the moments induced by off-axis forces with an instrumented strain tube.
- ♦ Designed two nozzle test articles
  - truncated ideal contour (TIC)
  - thrust optimized contour, specifically a parabolic (PAR) contour,



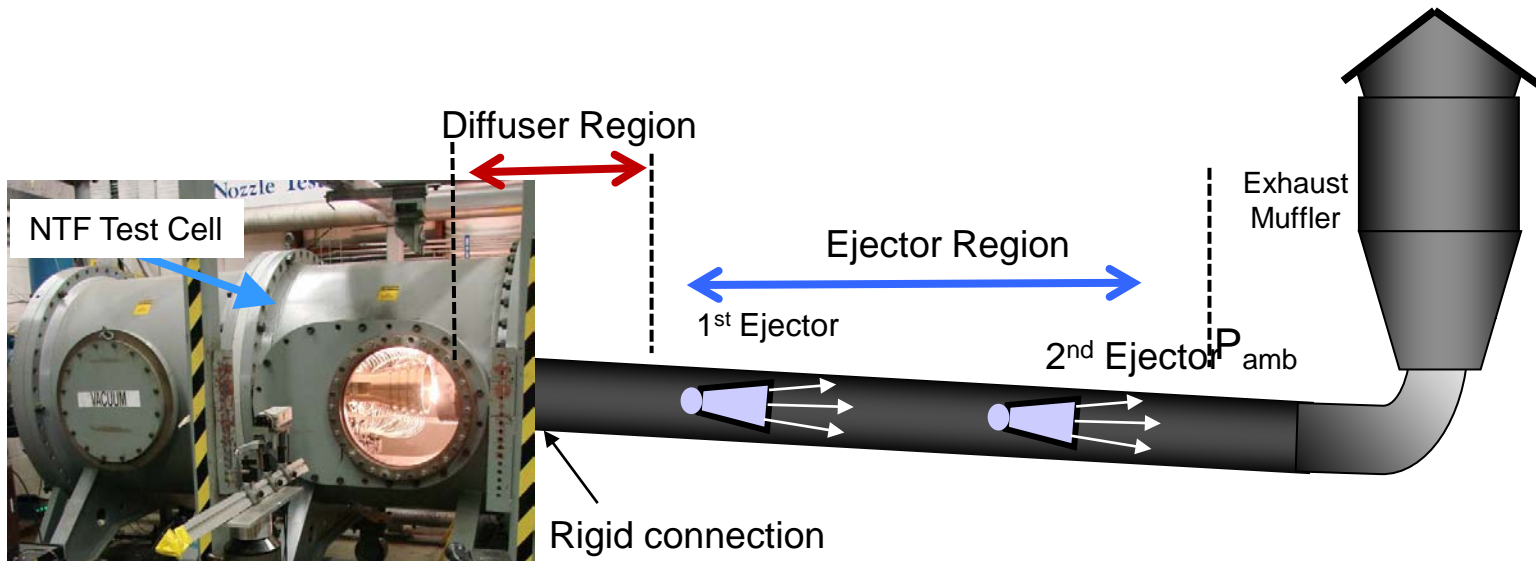
Test Article Installed

- ♦ In periods of increasing NPR, the chamber fills with air from the ejector pipe which is only inches from the end of the nozzle test article.
- ♦ This air impacts on the test article inducing strain in the strain tube. This backwash induced strain corrupts the SL moment measurement.
- ♦ The backwash's impact on the test data:
  - invalidates nozzle shutdown transients.
  - the 'up ramp' transients have to be assessed for continuously favorable  $dNPR/dt$ .

Flow in & out



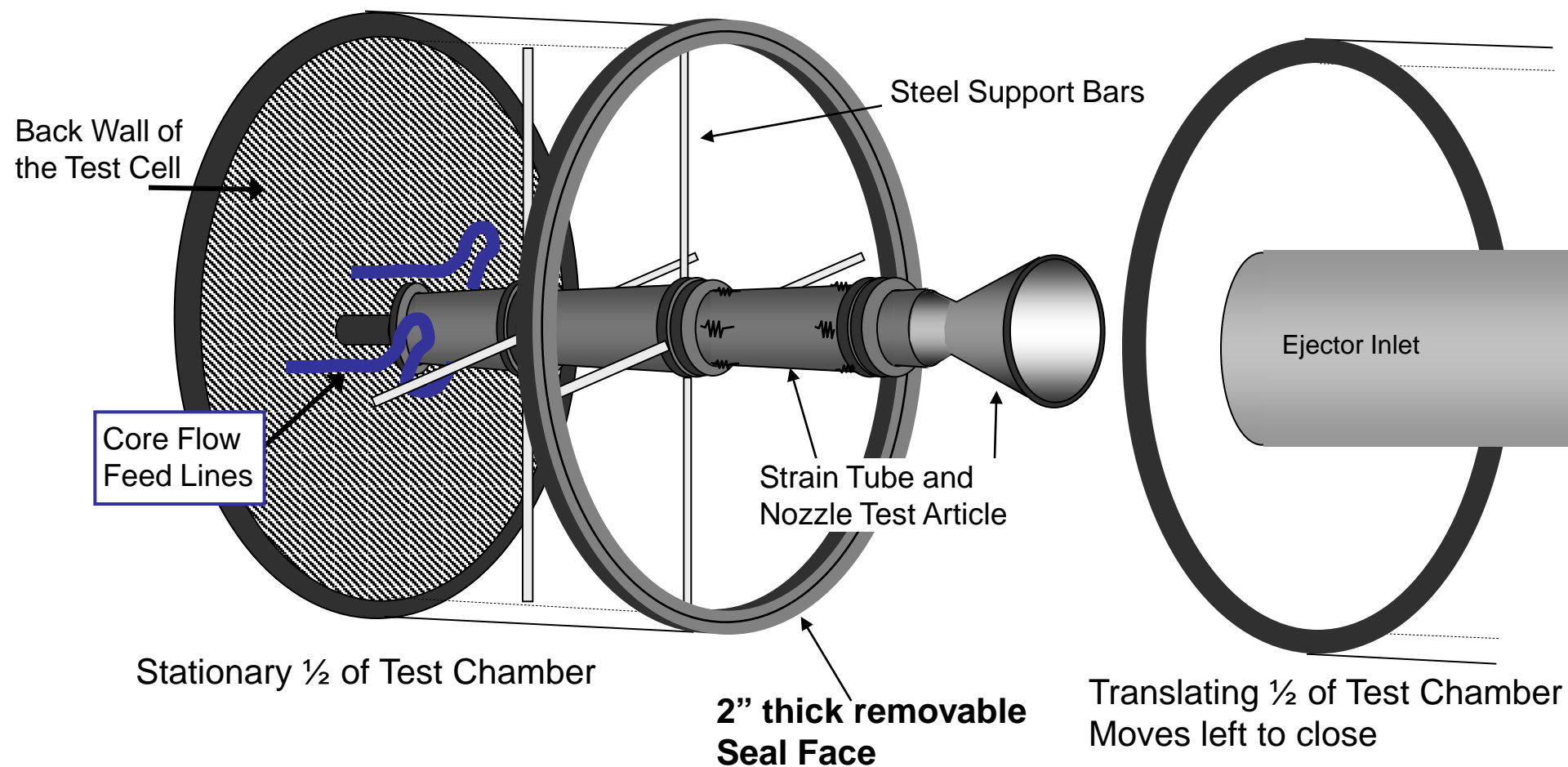
Ejector Pipe Inlet





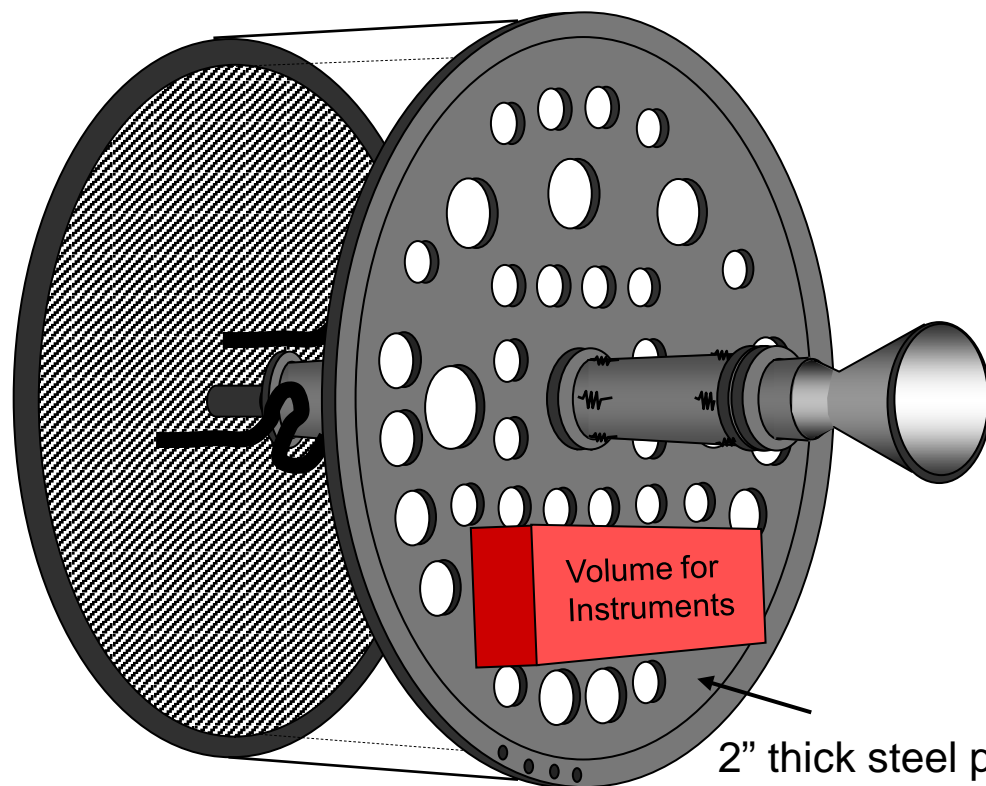
Schematic of the previous test article support system.

The old support system, intended for axial thrust measurement, could not be stiffened significantly.

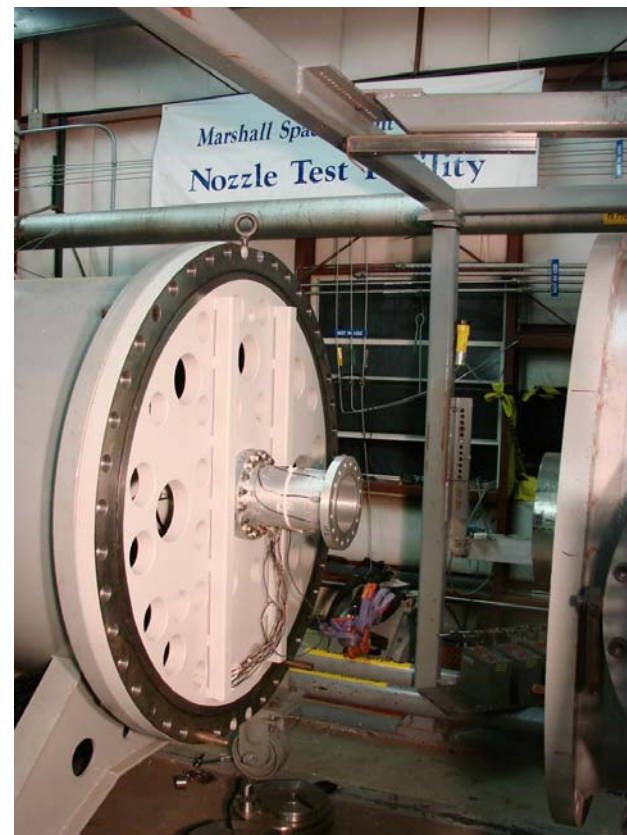


Schematic of the new test article support system.

- 2" thick seal face replaced with a 2" thick "Stiffener Plate".
- Dynamic analysis showed the plate provided the equivalent of a 'fixed end' for the strain tube.
- Test data later confirmed.



2" thick steel plate fits where the Seal Face was.

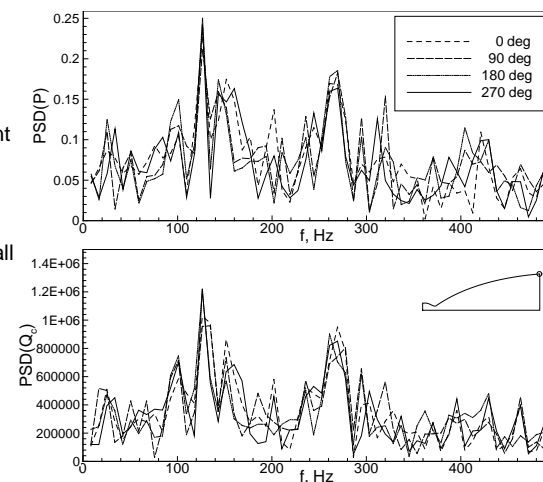
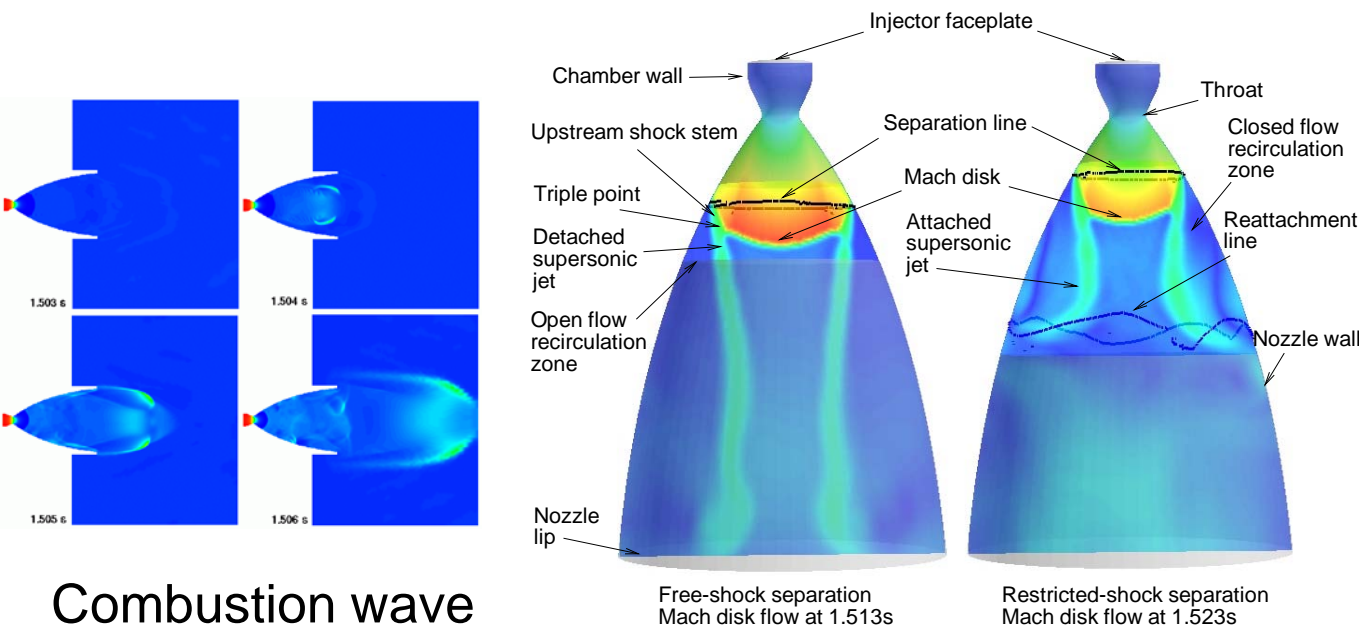
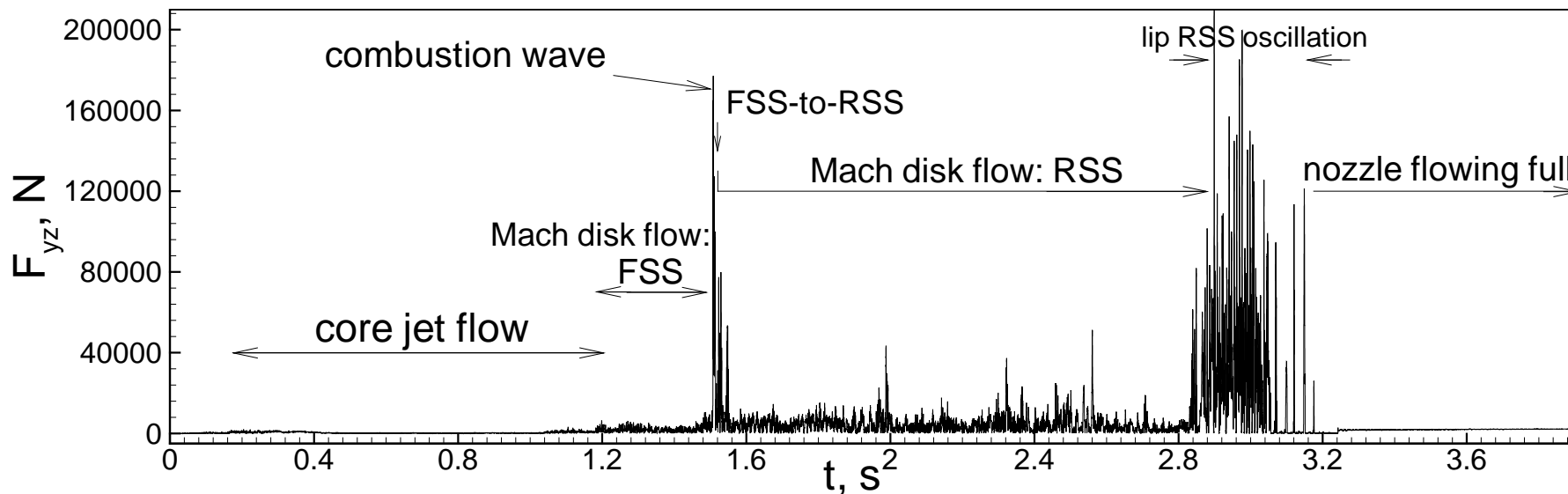




- Multidisciplinary computational methodology
  - UNIC time-accurate, unstructured-grid, pressure-based, reacting flow, CFD & heat transfer code
  - Engine system modeling for transient inlet properties (to simulate hot-firing tests)
  - Thermal modeling of wall temperatures for combustion chamber, nozzle, and nozzle extension (to simulate hot-firing tests)
- Benchmark or comparing results with available, actual rocket engine hot-firing
  - Benchmarked with a regeneratively cooled engine – SSME (side load physics captured: combustion wave, FSS-to-RSS and RSS-to-FSS transitions, cold wall promoted Coanda effect, RSS shock breathing)
  - Compared J-2X sea level results with another film cooled engine – LE-7A (side load captured: separation line jump)



# Benchmark with the Regeneratively Cooled SSME nozzle during Sea Level Startup



Combustion wave

FSS-to-RSS transition

Shock breathing frequency



# Benchmark with the Regeneratively Cooled SSME nozzle during Sea Level Startup



Fyz, kN			Dominant frequencies, Hz		Physics
	Test	CFD	Test	CFD	
1 <sup>st</sup> jump	90	80	-	-	FSS-to-RSS transition
2 <sup>nd</sup> jump	200	212	125	125	RSS breathing
			275	275	